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A REAL-TIME CONTROL APPROACH FOR MINE CLIMATE REGULATION

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Summary. We consider the problem of regulating the air quality in underground extraction rooms for mining industry. Based on distributed measurements, the goal is to minimize the energy consumption associated with the ventilation system to fulfil environmental constraints while ensuring thresholds on the admissible pollutants concentrations. This is clearly a challenging control problem where the flow dynamics, the interconnections between sub-systems and the time-varying topology have to be taken into account along with real-time computation constraints. In this paper, we first describe a real-time simulator based on simplified flow dynamics, which is used in a state-feedback control scheme that motivates model-based control strategies. An online parameter estimation algorithm is proposed to adjust the control-oriented model (pressure dynamics) output to the distributed measurements. A new approach based on time-delay systems is finally introduced to model the convective phenomena.

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1 INTRODUCTION

Mining ventilation is an interesting example of a large scale system with high environmental impact. Indeed, one of the first objectives of modern mining industry is to fulfil ecological specifications during the ore extraction and ore crushing, by optimizing the energy consumption or the production of polluting agents. This motivates the development of new control strategies for large scale aerodynamic processes based on appropriate automation and the consideration of the global system. More specifically, the approach presented in this paper is focused on the mining ventilation, as 50 % of the energy consumed by the mining process goes into the ventilation (including heating the air). It is clear that investigating automatic control solutions and minimizing the amount of pumped air to save energy consumption (proportional to the cube of airflow quantity) is of great environmental and industrial interest.

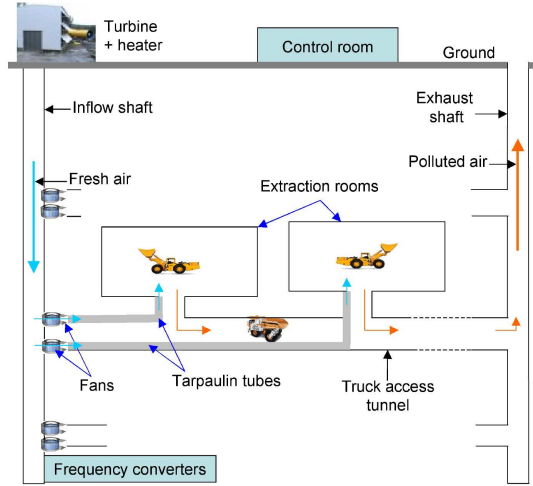


Fig. 1 Airflows in an underground mine.

The mine ventilation topology is illustrated in Fig. 1. It is first achieved by a turbine and a heater connected on the surface to a vertical shaft. The heater is introduced (in winter time at least) to avoid freezing in the upper part of the shaft and the air is cooled down at high depths (more than 1000 meters) because of the geothermal effect. We will refer to this part of the system as the *primary system*. From the ventilation shaft, fans located at each extraction level pump fresh air to the extraction rooms via tarpaulin tubes: this is the *secondary system*. Bad quality air naturally flows because of the pressure gradient from the extraction rooms back to the exhaust ventilation shaft (similar but separate from the primary ventilation shaft).

The distinction between primary and secondary systems is used to divide the control problems. In fact, the primary system typically has a clear geometry while the secondary system is strongly varying in geometry (rooms are blasted every day), characteristics (tarpaulin tube length and shape) and disturbances (trucks) even within

the same mine. Computational Fluid Dynamics (CFD) models, such as the one presented in [1], can then be envisioned for the primary system while grey-box identification or global models focused on the main dynamics should be preferred for the secondary one. Closed-loop control strategies have been proposed for the secondary system [2, 3], relying on distributed chemical measurements and embedded fan control. Their efficiency strongly depends on the available pressure in the vertical shaft, which is the topic of the present work.

We focus on the boundary control (turbine operation) of a deep well flow (vertical shaft) subject to distributed losses (fans exhausts). The paper is organized as follows. The physical properties and real-time simulator of the ventilation system is presented in Section 2, along with the main physical hypotheses. Section 3 introduces some first results on feedback control, stressing out the interest for advanced model-based control approaches. An estimation method that provides for an online tracking of the distributed dynamics parameters is introduced in Section 4. Finally, a novel approach based on time-delay systems suggest some new directions for real-time control in Section 5.

2 VENTILATION IN DEEP WELLS

Physical model and real-time simulator.

This section briefly summarizes the main results presented in [1], where a non-dimensional model was proposed thanks to the bond graph approach and a real-time simulator was described. The ventilation shafts are described by interconnected cells containing height-averaged flow values. Note that this is equivalent to a control volume discretization of the flow, where a single volume is used at each height. The equivalent bond graph description is then obtained for each cell by deriving a flow/effort model from Euler equation (see classical fluid dynamics textbooks such as [4] for a complete description):

$$\frac{\partial}{\partial t} \begin{bmatrix} \rho \\ \mathbf{M} \\ \rho E \end{bmatrix} + \nabla \cdot \begin{bmatrix} \mathbf{M} \\ \mathbf{M}^T \otimes \mathbf{V} + p\mathbf{I} \\ \mathbf{M}H \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \dot{q} \end{bmatrix}, \quad (1)$$

where ρ is the density, $\mathbf{M} = \rho\mathbf{V}$ (\mathbf{V} being the flow speed) the momentum, p the pressure, E the energy (per unit mass), \otimes the tensor product of two vectors, H the total enthalpy and \dot{q} is the rate of heat addition (see [5] for a precise description). This description is complemented with the perfect gas equation of state $p = \rho RT$, where R the specific gas constant and T the temperature. We make the following hypotheses:

- *H1*) in the momentum equation, the impulsive term is negligible compared to the pressure: $\rho v^2 \ll p$ and the dynamics is approximated with an algebraic relationship (i.e. Saint-Venant);
- *H2*) only the static pressure is considered, implying that the kinetic energy term in the energy conservation equation is omitted: $H = E + p/\rho$;
- *H3*) the gas is calorically perfect: $E = c_v T$, where $c_v = R/(\gamma - 1)$ ($\gamma = 1.4$) is the specific heat at constant volume.

The mine ventilation simulator is constructed based on this flow description and the fans models proposed in [6]. The ventilation shafts are both discretized with 28 control volumes and we consider 3 extraction levels. The regulation of the turbine and fans is done by setting their rotational speed, and flow speed, pressure and temperature can be measured in each control volume. This simulator (34 times faster than real-time in an Intel Centrino® 1.83 GHz PC) is used in the next sections to illustrate the estimation and control strategies.

Distributed pressure dynamics

For real-time control purposes, we are specifically interested in the pressure dynamics, which is the regulated variable. Note that the momentum can be obtained by implicit resolution of the Saint-Venant equation and used as an exogenous input for the other dynamics. A dedicated model is obtained from $H1 - H3$ and (1) by expressing the energy equation in terms of pressure (perfect gas equation) as:

$$\frac{\partial p}{\partial t} = -\frac{\partial}{\partial x} \left[\frac{M}{\rho} \cdot \left(1 + \frac{R}{c_v} \right) p \right] + \frac{R}{c_v} \dot{q}. \quad (2)$$

The energy losses are defined as pressure losses induced by the secondary system:

$$\dot{q}(x, t)R/c_v = s(t)\varrho_x(x)\Delta p_{fan}(t)\eta_{fan}(t) + r(t)p(x, t),$$

where ϱ_x is set by the mine topology (i.e. $\varrho_x = 1$ at the exhausts location and 0 otherwise), the vector Δp_{fan} contains the pressure gradients across each fan, η_{fan} is the blades rotational speed and r denotes the resistance on the shaft sides. Both $\Delta p_{fan}(t)$ and $\eta_{fan}(t)$ are considered as known engineering parameters.

3 FIRST RESULTS ON FEEDBACK CONTROL

The interest for advanced control strategies applied to the turbine operation regulation is investigated on a specific test case. We consider that a local PI (proportional and integral) feedback loop is set on the turbine so that its rotational speed is set according to a reference turbine pressure $p_{turb}(t)$, which consequently becomes the regulated variable. A second PI feedback loop is set on $p_{turb}(t)$ based on the difference $p_{ref} - p_{meas}$, where p_{ref} is the target pressure and $p_{meas}(t)$ is provided by pressure sensors.

The test case is defined as follows, for three extraction levels in a $L = 1100$ m deep mine. The 1st level fan (at $L/4$) is not operated, the 2nd level fan (at $L/2$) goes from 0 to 150 rpm at $t = 2000$ s and the 3rd level fan (at $3L/4$) is operated at 200 rpm. Pressure measurements at the turbine output and at the bottom of the well are available for feedback control.

Simulation results are presented in Fig. 2, where the turbine control (Fig. 2(a)) and regulated down pressure (Fig. 2(b)) signals using surface and bottom pressure measurements are depicted. The proportional gain is set to zero and the integral gain is 1/200. The objective is to ensure a bottom pressure of 1.1×10^5 Pa. From the control design and simulation results, we can observe that:

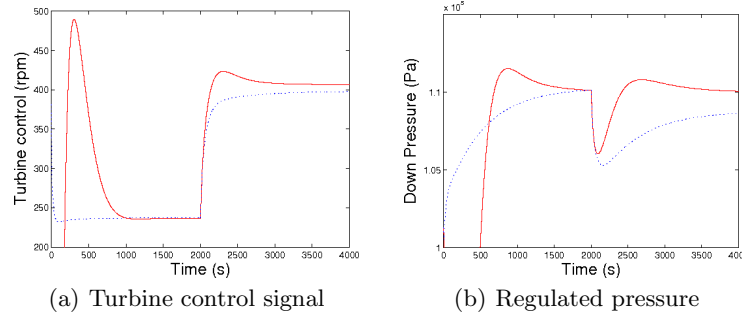


Fig. 2 Feedback control of the turbine rotational speed using top (blue dots) and bottom (red) pressure measurements.

- the closed-loop system is highly sensitive to the initial conditions (closed-loop behavior before $t = 1000s$);
- proportional feedback has a strong destabilizing effect and the integral action has to be handled with care;
- for given values of the controller gains, bottom measurements provide for a faster transient response and no steady-state error, in comparison with a feedback based on surface measurements.

The first two observations are related to the limitations associated with PI control and, implicitly, to the hypothesis that the well can be approximated as a linear time-invariant system (such hypothesis may be suggested from the step responses presented in [1], which are particularly smooth). This motivates further research on simplified time-varying models and model-based control approaches. The third observation emphasizes the importance of distributed measurements in the automation process.

4 DISTRIBUTED MEASUREMENTS AND ONLINE PARAMETERS ESTIMATION

We suppose that distributed measurements (i.e. obtained thanks to a wireless sensor network) are available to set the control law. One of the main advantages is the possibility to constrain a simplified model according to the behavior of the flow through the time-varying parameters describing the convective, resistive and source terms.

Control oriented model

We consider the volume-averaged impact of the momentum and density on the pressure dynamics, with $\bar{M}(t) = \frac{1}{V} \oint_{\mathcal{V}} M(v, t) dv$ and $\bar{\rho}(t) = \frac{1}{V} \oint_{\mathcal{V}} \rho(v, t) dv$, where \mathcal{V} is the shaft control volume. The physical model (2) is then approximated with the control-oriented model:

$$\frac{\partial \tilde{p}}{\partial t} = c(t) \frac{\partial \tilde{p}}{\partial x} + r(t) \tilde{p} + s(t) \varrho_x(x) \Delta p_{fan}(t) \eta_{fan}(t), \quad (3)$$

where $c(t) \doteq -\bar{M}(t)/\bar{\rho}(t) \cdot (1 + R/c_v)$. The boundary conditions are set by the inflow pressure ($\tilde{p}(0, t) = p_{in}(t)$) and the shaft dead end ($\partial\tilde{p}(L, t)/\partial x = 0$).

Online parameter estimation

Considering the class of systems that write as (3), our goal is to provide an estimation method for the time-varying parameters $\vartheta(t) \doteq \{c(t), r(t), s(t)\}$. In order to obtain a real-time estimation algorithm for ϑ , we define the cost function as:

$$J(\vartheta, t) = \frac{1}{2} \int_0^x \|p_{meas}(\theta, t) - \tilde{p}(\vartheta, \theta, t)\|_2^2 d\theta.$$

The output error is then minimized for $\vartheta^* \doteq \arg \min_{\vartheta} J(\vartheta, t)$. This optimization problem can be solved with a descent algorithm, using the sensitivity of $p(x, t)$ with respect to ϑ . For online estimation, the sensitivity has to be computed in real-time along with the model simulation. This is done thanks to the ordinary differential equation (ODE) method, where the sensitivity dynamics is given by:

$$\frac{d}{dt} \left[\frac{\partial \tilde{p}}{\partial \vartheta} \right] = \frac{\partial}{\partial \tilde{p}} \left[c(t) \frac{\partial \tilde{p}}{\partial x} + r(t) \tilde{p} \right] \frac{\partial \tilde{p}}{\partial \vartheta} + \left[\frac{\partial \tilde{p}}{\partial x} \tilde{p} - \varrho_x(x) \Delta p_{fan}(t) \eta_{fan}(t) \right].$$

The time evolution of the estimated parameters is then used to update (3) in parallel with the previous equation. The time-evolution of the convective, resistive and source

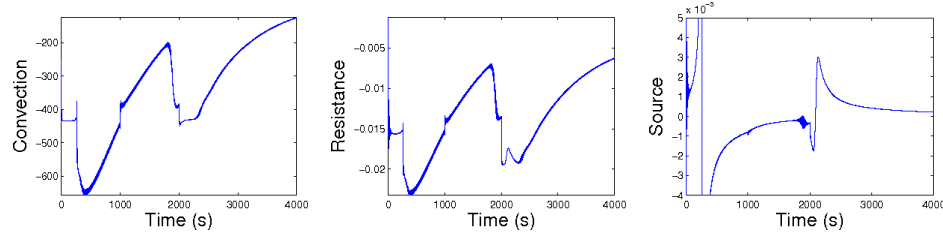


Fig. 3 Parameter estimation for the mine ventilation shaft.

terms is presented in Fig. 3. We can observe that, similarly to feedback control, the estimation strategy is highly sensitive to initial conditions and disturbances (3^{rd} fan operation at $t = 2000$ s). The time-varying nature of the system is illustrated by the large variation of the estimated parameters.

5 TIME-DELAY FORMULATION

While diffusion tends to stabilize the system, the convective effect is the main source of instability and/or poor closed-loop performance. This motivates the specific modeling approach presented in this section, where we show that a convective-resistive process can be associated with a time-delay model without discretizing the initial partial differential equation (PDE).

Initial PDE model

Consider some generic variable $p(\cdot, \cdot)$ described by the PDE:

$$\frac{\partial}{\partial t} p(t, x) + c(t) \frac{\partial}{\partial x} p(t, x) = r(t) p(t, x), \quad (4)$$

where $c(t)$ and $r(t)$ denote the appropriate speed and rate, respectively. It is assumed that both variables depend *only* on the time. If this PDE is used to describe the evolution of some physical quantity inside some generic compartment, then the boundary condition (BC) can be given by $p(t, 0) \doteq u(t)$, where u denotes some control (law) at the input (entry) of the compartment. For some constant $L > 0$, the initial condition (IC) can be given by $p(0, L) \doteq \psi(L)$, where ψ denotes an appropriate differentiable function and L is the generic length.

Method of characteristics

Define a new variable ξ by integrating $p(t, x)$ over the interval $[0, L]$. The variable ξ can describe, for instance, an average behavior of $p(\cdot, \cdot)$, that is $\xi(t) \doteq \int_0^L p(t, \eta) d\eta$. Thus, (4) rewrites as:

$$\frac{d}{dt} \xi(t) \doteq c(t) [u(t) - p(t, L)] + r(t) \xi(t), \quad (5)$$

which is an ODE in the new variable ξ . However, we need to rewrite this last ODE by avoiding the use of $p(t, L)$, which can be done thanks to the *method of characteristics*. This method is applied by introducing a new *independent* variable θ such that $p(\theta) \doteq p(t(\theta), x(\theta))$. It is easy to see that:

$$\frac{dp}{d\theta} \doteq \frac{\partial p}{\partial t} \cdot \frac{dt}{d\theta} + \frac{\partial p}{\partial x} \cdot \frac{dx}{d\theta},$$

and, consequently, $dt/d\theta = 1$, $dx/d\theta = c(t)$. It follows that $p(\cdot)$ is described by the ODE (in the new variable θ) $dp/d\theta = r(t)p$. The model parametric dependence for $t(\theta)$, $p(\theta)$ and $r(\theta)$ is obtained by integrating the previous variation laws.

The plane defined by the variables t and x can be separated in *two regions* by the curve, assumed sufficiently regular, corresponding to the system's evolution starting from the origin $\mathcal{O} = (0, 0) \mapsto \mathcal{C}_{\mathcal{O}}$ and parameterized as follows:

$$\mathcal{C}_{\mathcal{O}} \doteq \left\{ (t, x) : \quad t(\theta) = \theta, \quad x(\theta) = \int_0^\theta c(\eta) d\eta, \quad \forall \theta \in [0, \theta_f] \right\},$$

where θ_f corresponds to $L \doteq \int_0^{\theta_f} c(\eta) d\eta$. Denoting \mathcal{R}_+ (\mathcal{R}_-) the region situated above (below) the curve $\mathcal{C}_{\mathcal{O}}$ in the parameter space defined by (t, x) , the *method of characteristics* leads to:

$$p(t, L) \doteq \begin{cases} \psi \left(L - \int_0^t c(\eta) d\eta \right) \exp \left(\int_0^t r(\eta) d\eta \right), & \text{if } (t, x) \in \mathcal{R}_+, \\ u(t - \theta_f) \exp \left(\int_0^{\theta_f} r(\eta) d\eta \right), & \text{if } (t, x) \in \mathcal{R}_-. \end{cases}$$

Since our main interest is related to long time behaviour (stability, etc.), we are concentrating only on the region \mathcal{R}_- that includes the time-axis.

Delay differential equation

A simple substitution of the corresponding $p(t, L)$ in (5) leads to the following ODE:

$$\frac{d}{dt}\xi = c(t) \left[u(t) - u(t - \theta_f) \exp \left(\int_0^{\theta_f} r(\eta) d\eta \right) \right] + r(t)\xi(t).$$

If r and c are *constant*, we obtain the delay differential equation (DDE):

$$\dot{\xi}(t) = c \left[u(t) - u(t - L/c) e^{rL/c} \right] + r\xi(t). \quad (6)$$

It is interesting to observe the influence of c and r in (6): they scale the convection-dependant delayed input according to the state fundamental dynamics.

CONCLUSIONS

In this work, we proposed a novel real-time control approach for climate regulation in mines. First results on output feedback motivated a model-based approach to this problem and the need for advanced control methodologies. We focused on the pressure control for the main ventilation shaft and proposed a new control-oriented model. Online estimation of the time-varying model parameters and a time-delay approach were introduced. This work sets the problem formulation and the main directions for further research on dedicated control strategies.

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